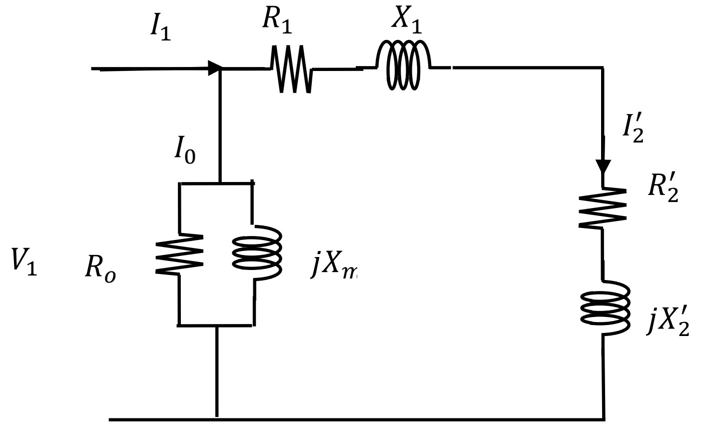
Starting methods of 3-∅ induction motor

At starting, the voltage induced in the induction motor rotor is maximum (s = 1). Since the rotor impedance is low, the rotor current is excessively large. This large rotor current is reflected in the stator because of transformer action. This results in high starting current (5 to 8 times the full-load current) in the stator at low power factor and consequently the value of starting torque is low and starting current is high.

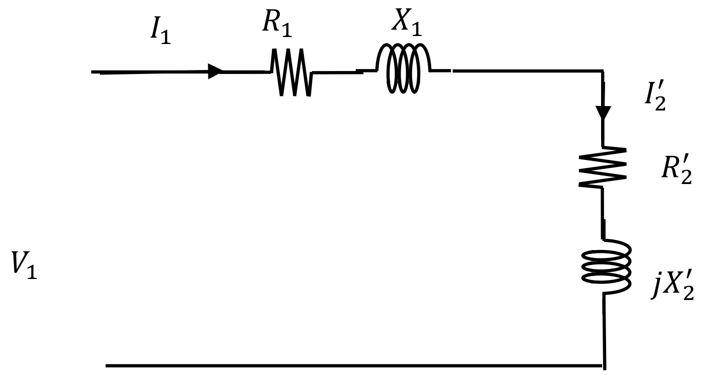
Necessity of External starting methods

The purpose of starters in case of three phase induction motor as name says is not to start the motor as , three phase induction motors are basically self-starting motors. The purpose of starters is to limit high starting current. Three phase induction motors draws very high starting current, if such high current flows through the winding for longer time, the motor winding will be damaged. Hence to limit such a high starting current, starters are required.

Why the starting current drawn by the motor is high?
Starting current of induction motor is as high as 5 to 7 times the normal full load current. Therefore different starting of induction motor, methods such as (star delta starter, auto transformer starter and other starting methods) are employed in order to reduce the **high starting currents of induction motor**.



As I_0 is less than I_2'



$$I_1 = I_2' = \frac{230.9}{\sqrt{0.27^2 + 0.9^2}} = 245A$$

Such a high current, will damage the winding, if flows for longer time, and also have high line drops, which may be effect the performance of other equipment's connected in parallel.

Disadvantages of High Starting Currents in Induction Motor

(i) For rating of ≤5H.P rotor is in smaller size inertia required is also small. Whenever voltage supply is given I_{sc} flows high current flows and speed raises quickly and also slip raises quickly so $R_2'\left(\frac{1}{S}-1\right)$ is build up. So for this no need of starting method. $R_2'\left(\frac{1}{S}-1\right)$ increases faster rate so I_{sc} decreases. So I_{sc} current not is flowing through windings for longer periods it flows only for shorter periods for this no need of starters. But such high inrush currents drawn by induction motor during starting can result in large dip in connected bus voltages

(ii) For large induction motors > 5H.P , the diameter of rotor is large, inertia is also large, so speed builds up at smaller rate , I_{sc} current flows for a larger time. This may damage the windings as slip decreases slowly and as $R_2'\left(\frac{1}{S}-1\right)$ builds up slowly.

Note:

(1) High inrush currents drawn by induction motor during starting can result in large dip in connected bus voltages. This dip in bus voltages can impact the performance of other motors operating on the bus. Voltage dips during starting of large motors can trip some of the motors operating on the same bus. Care should be taken to limit the inrush currents during starting of the motor by employing proper starting methods.

☞ ***One of the most noticeable effect of full voltage starting is the dimming or flickering of lights while the motor is starting.***

(2) For large motors life of the machine depends on the number of starting. High inrush currents can cause increase in the temperature of the machine, damages the insulation and can reduce the life of the machine

How to control the starting current

Since starting current is determined by the impedance of the motor while starting, reduction of the stator voltage will reduce the starting current requirement. If the starting voltage is reduced to 40% of its nominal value, the starting current will also be reduced by the same percentage, in accordance with ohm's law, $I=V/Z_{01}$, where I_{sc} is the starting current, V is the voltage applied to the motor and Z_{01} is the locked rotor impedance of the motor, since Z_{01} is essentially a fixed value at the instant of starting, and change in voltage will direct effect the starting current.

By reducing the starting voltage at the motor terminals, starting torque is decreased. The starting torque at standstill of a squirrel cage induction motor is approximately proportional to the square of the applied voltage. This is given by the equation $T=KV^2$, where T is the torque at standstill, K is a constant determined by the particular motor and V is the voltage applied to the stator winding

Relationship between Starting torque to full load torque in terms of current: $\frac{T_{st}}{T_{fl}}$

At starting, torque, T= T_{st}, $I_2=I_{st}$; therefore starting torque, $T_{st}= kI_{st}^2 \frac{R_2}{1}$

At Full load, torque $T=T_{fl}$, $I_2=I_{fl}$; full load torque, $T_{fl}= kI_{fl}^2 \frac{R_2}{s_{fl}}$

$$\frac{T_{st}}{T_{fl}} = \left(\frac{I_{st}}{I_{fl}}\right)^2 s_{fl}$$

Methods of Starting 3-Phase Induction Motors

The method to be employed in starting a given induction motor depends upon the size of the motor and the type of the motor. The common methods used to start induction motors are:

(i) Direct-on-line starting
(ii) Stator resistance starting
(iii) Autotransformer starting
(iv) Star-delta starting
(v) Rotor resistance starting

Methods (i) to (iv) are applicable to both squirrel-cage and slip ring motors. However, method (v) is applicable only to slip ring motors. In practice, any one of the first four methods is used for starting squirrel cage motors, depending upon ,the size of the motor. But slip ring motors are invariably started by rotor resistance starting.

Methods of Starting Squirrel-Cage Motors

Except direct-on-line starting, all other methods of starting squirrel-cage motors employ reduced voltage across motor terminals at starting.

Direct online starting

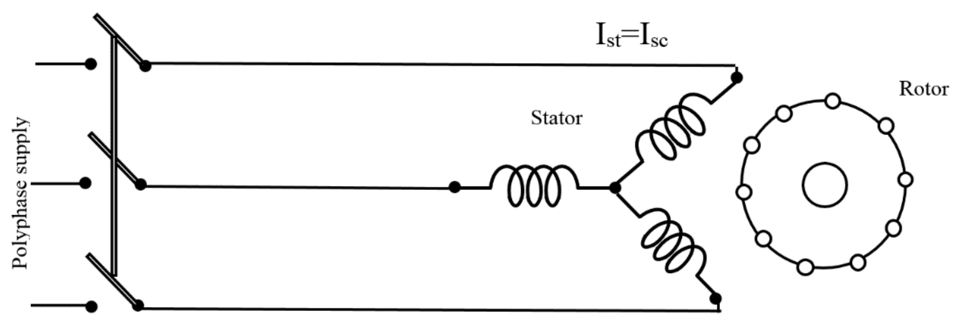
This method can be used to start small induction motors up to 5H.P

$$I_{st} = I_{sc}$$

$$\frac{T_{st}}{T_{fl}} = S_{fl}\left(\frac{I_{sc}}{I_{fl}}\right)^2$$

DOL Starter to protective devices are employed

1. Low voltage Relay
2. Over current/ over voltage relay



External starting methods- Reduced Voltage

In external starting method applied voltage to the induction motor should be reduced at the time of starting by using some arrangement.

1. Series reactor/resistor method
2. Auto transformer method
3. Star/ delta method

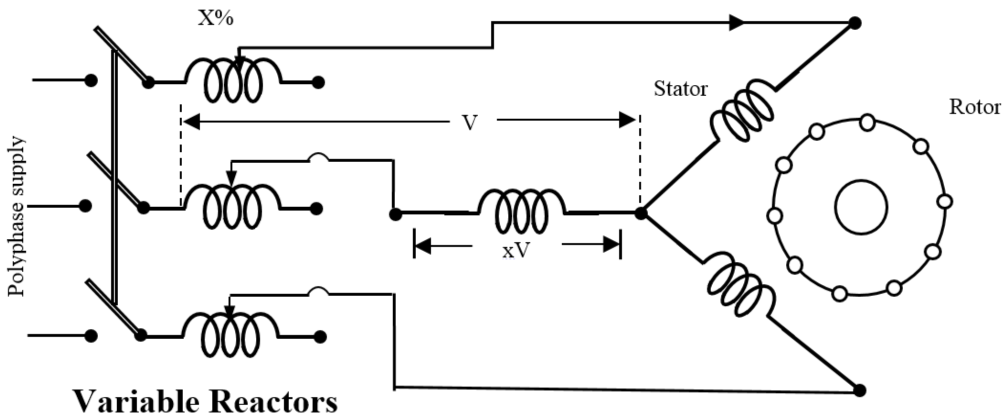
1. Series reactor/ resistor method of starting:

In this method, ***external resistances*** are connected in series with each phase of stator winding during starting. This causes voltage drop across the resistances so that voltage available across motor terminals is reduced and hence the starting current. The starting resistances are gradually cut out in steps (two or more steps) from the stator circuit as the motor picks up speed. When the motor attains rated speed, the resistances are completely cut out and full line voltage is applied to the rotor

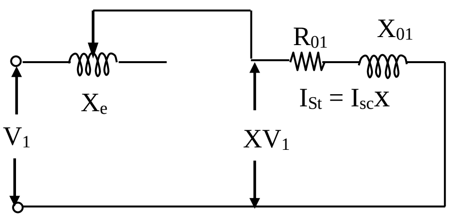
Voltage is reduced to xV

Therefore I_{st} is reduced to xI_{SC}

$$I_{st} = KI_{sc}$$



Variable Reactors



$$\cos\phi = \frac{R}{Z} \quad X_e \uparrow \rightarrow Z\uparrow$$

$$\therefore \text{ Cos}\phi \downarrow$$

$$\mathrm{I_{st}} = \frac{\mathrm{xV_1}}{\mathrm{Z_{01}}}$$

$$I_{st} = xI_{sc}$$

In this method if the applied voltage is reduced to fraction *x* the starting current also reduce to fraction *x*

$$\frac{T_{st}}{T_{fl}} = x^2\left(\frac{I_{sc}}{I_{fl}}\right)^2 s_{fl}$$

In this method starting current reduces to fraction *x* when compared to *DOL* method of starting and the starting torque reduces fraction x^2 when compared to *DOL* method of starting.

Applications:

(i) As starting torque reduction is more when compared to starting current reduction. This method cannot be used to start induction motors for high starting torque demand loads.

(ii) This method can be used to start low starting torque demand such as ex: pump, fans type of load.

Drawbacks

- ❖ The main drawback of series reactor method of starting is it reduces starting power of induction motor.
- ❖ In order to overcome the above difficulty series resistance should be used in place of series reactors.
- ❖ The other drawback of series resistor method of starting it reduces efficiency of induction motor at the time of starting due to additional power loss.

2. Auto transformer method of starting

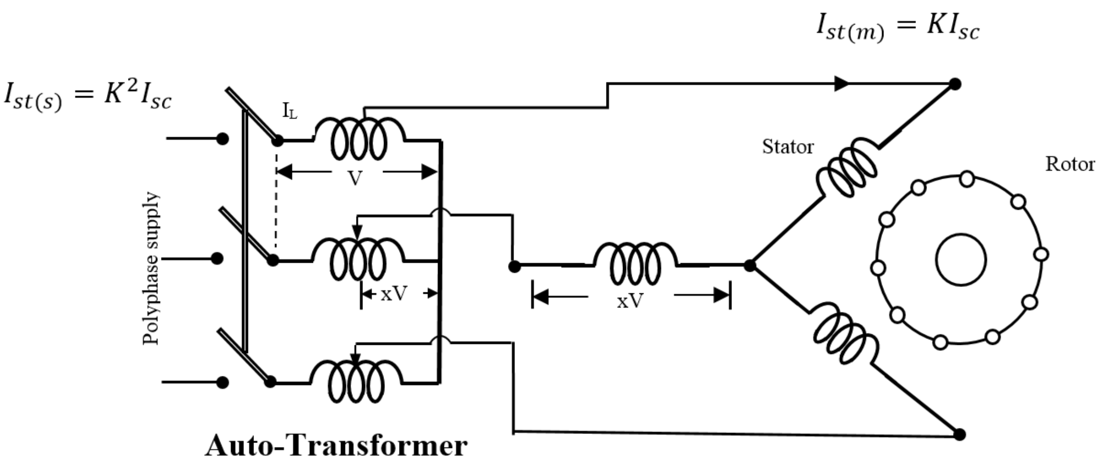
Auto transformer tapping of *K*%

I_{Sc}-short circuit line current V

$(KVA)_{AT}=\sqrt{3}V_L I$

$= \sqrt{3}KVKI_{sc}=\sqrt{3}VK^2I_{sc}$

Starting current of stator from Auto T/F = xI_{Sc}; Starting current of set from line = x^2 I_{SC}



In this method if an auto transformer with a percentage tapping of K% is used. Starting current drawn by induction motor reduces fraction K% when compared to DOL starting. In this process

the starting current drawn by auto transformer from source is reduce to fraction$K^2 I_{sc}$. When compared to DOL method of starting this can be treated as starting current of this source.
Starting torque/full load torque ratio

$$\frac{T_{st}}{T_{fl}} = S_{fl}\left(\frac{I_{st}}{I_{fl}}\right)^2$$

$$\frac{T_{st}}{T_{fl}} = K^2\left(\frac{I_{sc}}{I_{fl}}\right)^2 S_{fl}$$

In this method starting torque reduces to fraction K^2 when compared to DOL method of starting.
For same reduction in starting torque auto transformer of starting reduces the starting current by a further fraction K. when compared to series reactor/resistor method of starting.As starting current reduction is more in auto transformer for some current reduction when compared to series reactor method of starting. This method can be used to start induction motor which handles high starting torque loads.

Advantages:

1. Produces the maximum torque per ampere of line current-no other starting method for squirrel-cage motors produce more.
2. Maximum reduction of inrush current- more than any other
3. Taps on auto transformer permit starting voltage to be changed.

Drawbacks:

1. It is used not for induction motors.

☞ ***Autotransformer starters are the first choice where maximum starting torque or minimum starting current is a consideration. When starting is frequent or acceleration is long, these starters rate very high. Taps permit adjustment of starting current or torque.***

3. Star/Delta starting methods

This method is applicable to start the induction motor whose stator windings are designed to operate with delta under running condition.

Direct delta starting

$$I_{st(phase)} = \frac{V_1}{Z_{01}}$$

$$\sqrt{3} I_{st(phase)} = I_{st(line)} = \frac{\sqrt{3} V_1}{Z_{01}}$$

Star connected starting

$$I_{st(line)} = I_{st(phase)}$$

$$I_{st(phase)} = \frac{V_1}{\sqrt{3} Z_{01}}$$

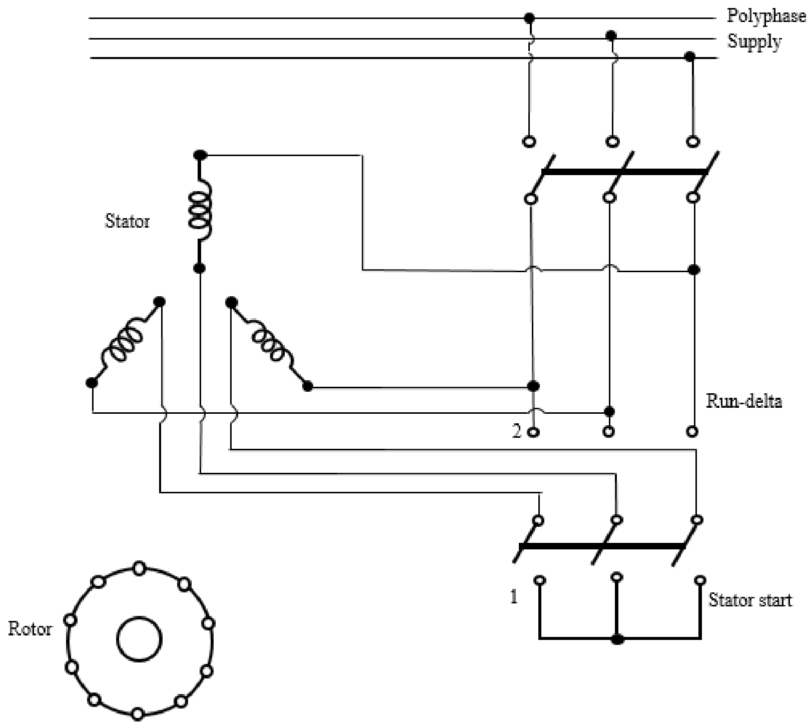
$$\frac{I_{st(star)}}{I_{st(delta)}} = \frac{\frac{V_1}{\sqrt{3}Z_{01}}}{\frac{\sqrt{3}V_1}{Z_{01}}} = \frac{1}{3}$$

The starting current with star starting is just 1/3rd when compared to direct delta starting.

$$\frac{T_{st}}{T_{fl}} = S_{fl}\left(\frac{I_{st}}{I_{fl}}\right)^2$$

$$\frac{T_{st}}{T_{fl}} = \frac{1}{3}S_{fl}\left(\frac{I_{sc}}{I_{fl}}\right)^2$$

Starting torque also reduces to 1/3rd when compared direct on line starting.



The star/delta starter is equivalent to auto transformer with a 57.7% tapping. The change over star to delta should take at more than 50% of rated speed. If any attempt is made to change the switch from star to delta before motor reaches 80% of full load. There is a possibly damage of stator windings.

Advantages

1. Produces high torque per ampere of line current
2. Inexpensive
3. No heat producing or current changing device used

Disadvantages

1. A special motor is required
2. Starting torque is fixed at 1/3 of delta connected(full voltage) starting torque

☞ ***Wye-Delta is advantageous where the required starting torque is low and where the line current drawn must be at a minimum. A typical application is a centrifugal***

compressor, on which compression is delayed (by a value) until line voltage connection of the motor has been completed

1 ***A small 3ϕ IM has a short circuit current equal to 5 times full load current. Determine the starting current and starting torque if resistance starter is used to reduce the impressed voltage to 60% of normal voltage. The full load slip is 0.05***

Sol:

$$\frac{T_{st}}{T_{fl}} = \left(\frac{I_{st}}{I_{fl}}\right)^2 s_{fl}$$

Given $I_{sc}=5I_{fl}$ and $x=0.6$, $s_{fl}=0.05$
For resistance starters
We have

$$\frac{T_{st}}{T_{fl}} = \left(\frac{I_{st}}{I_{fl}}\right)^2 s_{fl}$$

and $I_{st}=xI_{sc}$

$$\frac{T_{st}}{T_{fl}} = x^2\left(\frac{I_{sc}}{I_{fl}}\right)^2 s_{fl} = 0.6^2\left(\frac{5I_{fl}}{I_{fl}}\right)^2 \times 0.05 = 0.45$$

2 ***A cage IM When started by means of a Y - Δ starter takes 180% of FL line current & develops 35% of FL torque at starting. Calculate the starting torque & current in terms of FL values, if an auto T/f with 75% tapping were employed.***

(a) Y-Δ starting

Line current with direct ON – line starting

I_{sc} $= 3 \times 180\%$ of I_{fl}

$= 3 \times 1.8\, I_{fl}$

$= 5.4\, I_{fl}$

$$\frac{T_{st}}{T_{fl}} = \frac{1}{3}\left(\frac{I_{SC}}{I_{fl}}\right)^2 S_{fl}$$

$$0.35 = \frac{1}{3}(5.4)^2 S_{fl}$$

(b) Auto – T/F starting

$Ist = x^2 I_{SC} = (0.75)^2 \times 5.4 I_{fl}$

$= 3.0375 I_{fl}$

$$\frac{T_{st}}{T_{fl}} = x^2\left(\frac{I_{SC}}{I_{fl}}\right)^2 S_{fl}$$

$= (0.75)^2 \times (5.4)^2 S_{fl}$

$= (0.75)^2 \times 3 \times 0.35$

$= 0.59$

T_{st} = 59% of FL Torque.

Determine the suitable tapping on an auto T/F starter for an IM required to start the Motor with 40% of FL torque. The short circuit current of the motor is 5 times the FL current & FL slip is 0.035: Also determine the current drawn from the mains as a fraction of FL current

$$T_{st} = x^2\left(\frac{I_{sc}}{I_{fl}}\right)^2 s_{fl}\, T_{fl}$$

$0.4T_{fl} = x^2(5)^2(0.035T_{fl})$

$x = 0.676$

Current drawn from the supply

$= x^2 I_{SC}$

$= 0.457 \times 5 \times I_{fl}$

$= 2.28I_{fl}$

A cage IM has a FL slip of 0.05. The motor starting current at rated voltage is 5.5 times FL current. Find the toppings on the auto – T/F starter which could give FL torque at start. Also find the line current at starting.

$$\frac{T_{est}}{T_{efl}} = x^2\left(\frac{I_{SC}}{I_{fl}}\right)^2 S_{fl}$$

$$1 = x^2\left(\frac{5.5I_{fl}}{I_{fl}}\right)^2 \times 0.05$$

$x = 0.0813$ or 81.3% tapping

tapping current $I_{st} = x^2 I_{SC} = (0.813)^2(5T_{fl})$

$= 3.3T_{fl}$

A 3ϕ cage IM has a short circuit current equal to 5 times FL current. Find the starting torque as a percentage of FL torque if the motor is started by (i) direct switching to supply (ii) start delta starter (iii) an Auto T/F. (iv) a resistance in stator circuit. The starting current in (iii) & (v) is limited to 2.5 times the FL current & the FL slip is 4%

(i) Starting torque with direct switching

$$T_{st} = \left(\frac{T_{SC}}{I_{fl}}\right)^2 S_{fl}\, T_{fl}$$

$\Rightarrow (5)^2 \times 0.04\ T_{fl} = T_{fl}$

(ii) Starting torque with Y - Δ starter

$$T_{st} = \frac{1}{3}\left(\frac{I_{SC}}{I_{fl}}\right)^2 S_{fl}\, T_{fl}$$

$= \frac{1}{3}(5)^2 \times 0.04T_{fl}$

$= \frac{1}{3}T_{fl}$

$= \frac{100}{3}T_{fl}\%$

$= 33.3\%$ of T_{gl}

(iii)Current taken from supply by auto – T/F

$I_{stl} = x^2 I_{SC}$

Also,

$I^1_{stl} = 2.5I_{fl}$

$\therefore\ x^2 I_{SC} = 2.5I_{fl}$

But,

$I_{SC} = sI_{fl}$ (given)

$\therefore\ x^2 \times sI_{fl} = 2.5I_{fl}$ & $x^2 = 0.5$

Starting torque with auto – T/F starter

$$T_{st} = x^2\left(\frac{I_{SC}}{I_{fl}}\right)^2 S_{fl}T_{fl}$$

$$= \frac{1}{2}(5)^2 \times 0.04T_{fl} = 0.5T_{fl}$$

$\therefore\ T_{st}$ = 50% of FL torque

(iv) Starting Torque with a resistance in stator circuit.

$$T_{st} = \left(\frac{I_{st}}{I_{fl}}\right)^2 S_{fl}T_{fl}$$

$= (2.5)^2\ 0.04T_{fl}$

$= 0.25T_{fl}$

T_{st} = 25% of FL Torque

Find the percentage tapping required on an auto- T/F reputed for a squirrel cage motor to start the motor against ¼ of FL torque. The short circuit current on normal voltage is 4 times FL current & FL slip is 3%.

$\frac{T_{st}}{T_f} = \frac{1}{4}$, $\frac{I_{SC}}{I_f} = 4$, $S_f = 0.03$

$$\therefore\ \frac{T_{st}}{T_f} = k^2\left(\frac{I_{SC}}{I_f}\right)^2 S_f$$

$\Rightarrow \frac{1}{4} = k^2 \times 4^2 \times 0.03$

K = 72.2%

A 3ϕ, 6 pole 50Hz IM takes 60A at FL speed of 940 rpm & develops a torque of 150 Nm. The starting current at rated voltage is 300A. What is the starting torque? If a Y-Δ starter is used, determine starting torque & starting current.

For direct – switching of induction Motors

$$\frac{T_{st}}{T_f} = \left(\frac{I_{SC}}{I_f}\right)^2 S_{fl}$$

Here,

$I_{st} = I_{SC} = 300A$ (line value)
$I_f = 60A$ (line value)
$S_f = \frac{1000 - 940}{1000} = 0.06$
$T_f = 150$ N-m
$\therefore\ T_{st} = 150\left(\frac{300}{60}\right)^2 \times 0.06$
$= 225$ N-m
When Y- starter is used starting current = 1/3 × starting current with direct starting = $\frac{300}{3}$
= 100A
Starting torque = 225/3
= 75N-m.

A small squirrel cage IM has a starting current of 6 times FL current & FL slip of 0.05. Find in pu or FL value, the current (line) & starting torque with the following methods of starting (a) to (d).
(a) Direct switching
(b) Stator – resistance starting with motor current limited to 2 pu
(c) Auto T/F starting with motor current limited to 2 pu &
(d) Star – delta starting
(e) What auto T/F ratio would give 1 pu starting torque.

(a) $I_S = 6$ pu
$T_S = (6)^2 \times 0.05$
$= 1.8$
(b) $I_s = 2$ pu
$T_S = (2)^2 \times 0.05$
$= 0.2$ pu

(c) $x = 2/6 = \frac{1}{3}$
$I_S(\text{motor}) = 2\text{pu}$
$I_{s(\text{line})} = \frac{1}{3} \times 2\ \text{pu} = 0.67\text{pu}$

$T_s = (2)^2 \times (0.05)$
$= 0.02$ pu

(d) $I_S = \frac{1}{3} \times 6 = 2\text{pu}$
$T_S = \frac{1}{3}(6)^2 \times 0.05$
$= 0.6\text{pu}$

(e) $T_S = x^2(6)^2 \times 0.05$
$= 1$ pu
$x = 0.745(\approx 75\%$ tap)

Determine approximately the starting torque of an IM in terms of FL torque when started by means of (a) Y - Δ switch (b) an auto T/F with 70.7% tapping. The short circuit current of the motor at normal voltage is 6 times FL current & FL slip is 4% neglect magnetizing current.

(a) $\frac{T_{st}}{T_{fl}} = \frac{1}{3}\left(\frac{I_{SC}}{I_{fl}}\right)^2 S_f$

$= \frac{1}{3} \times 6^2 \times 0.04 = 0.48$

$T_{St} = 0.48T_f$ or 48% or FL value

(b) Here K = 0.707 = $\frac{1}{\sqrt{2}}$; $K^2 = \frac{1}{2}$

Now $\frac{T_{st}}{T_{fl}} = K^2\left(\frac{I_{SC}}{I_f}\right)^2 S_f$

$= \frac{1}{2} \times 6 \times 0.04 = 0.72$

$T_{st} = 0.72T_{fl}$ or 72% of T_{fl}.

Speed control techniques of 3-ϕ induction motor

Induction motors are the most widely used motors for appliances, industrial control, and automation; hence, they are often called the workhorse of the motion industry. They are robust, reliable, and durable. When power is supplied to an induction motor at the optional specifications, it runs at its rated speed. However, many applications need variable speed operations.

1. Speed control is required for smooth starting and smooth stopping of electrical load (mechanical loads).
2. Power saving is also possible by using speed control technique, so that efficiency can be maintained.

The basic speed equation for three phase induction motor is

$$N_r = N_s(1 - S)$$

From the above equation, we can say the speed of the motor can be controlled either by controlling the synchronous speed or the slip

Control from stator side

(a) Stator voltage control

(b) Pole changing method

(c) Frequency control

- (i) Constant flux control/ (v/f) control/ variable voltage and variable frequency control
- (ii) Variable flux/ flux weakening control

Control from rotor side

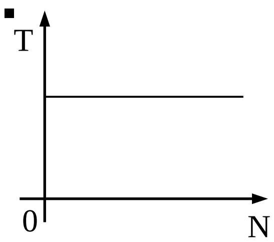
(u) Rotor resistance control

(v) By injecting emf in the rotor circuit

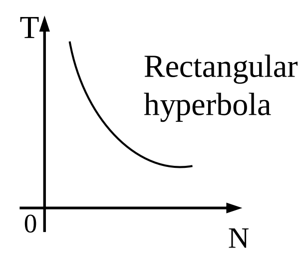
(w) By cascade connection

Behavior of induction motor during speed control

1. Constant torque variable power mode drive
2. Constant power variable torque mode drive



- ➢The drive used for this type of load is called constant torque variable power drive.
- ➢ This drive is suitable to control the speed less than rated speed.
- ➢ In D.C machine the technique used for this is Armature control technique.



- ➢The drive used for this type of load is called constant power variable torque drive.
- ➢ This drive is suitable to control the speed above the rated speed.
- ➢ In D.C machine the technique used for this is flux control technique.

a) Voltage control Technique:

f= f_{rated} (constant), Applied reduced voltage V_1<V_{rated} (under load condition of machine)

$$T \propto \frac{SV_1^2}{R_2}$$
$$SV_1^2 = k$$
$$V_1^2 \propto \frac{1}{S}$$

Voltage decreases so slip increases so speed decreases/falls

$$N = N_s(1-s)$$

- In this voltage control technique by keeping frequency constant the applied voltage to an induction motor should be reduced below its rated value under load condition to control the speed.
- If applied voltage reduces by keeping frequency constant slip of the induction motor decreases to maintain load torque constant. Then by speed of induction motor falls below its rated value.

  A 6- pole induction motor is operating at 400V, 50Hz and N_1 = 950 rpm, when the voltage is reduced to 300V find the motor speed for constant torque.

  $s_1 = 0.05$ and $s_1v_1^2=s_2v_2^2$

  $(0.05)(400)^2 = s_2\,(300)^{2;}$ $s_2 = 0.08$

  $\therefore N_{r2} = N_{S2}\,(1-s_2) = 920$ rpm
- By using this method speeds below the rated value can only be achieved.
- During voltage control, induction motor acts as constant torque variable power drive.

$$T=\text{constant}$$
$$sV_1^2 = \text{constant}$$
$$s_1V_1^2 = s_2V_2^2$$

Drawbacks of voltage control technique

1. $\overline{I_1}=\overline{I_0}+\overline{I_2'}$ I_0 is neglected

$I_1=I_2'$

$$= \frac{E_2'}{\sqrt{\left(\frac{R_2'}{s}\right)^2 + (X_2')^2}}$$

If s is low $\frac{R_2'}{s} \gg X_2'$

$$I_1 \cong \frac{E_2^1}{\left(\frac{R_2'}{s}\right)}$$
$$I_1 \propto \frac{sV_1}{R_2'}$$

Slip is doubled → voltage reduction is $\frac{1}{\sqrt{2}}$ to maintain the load torque constant.

$$I_1 \propto \frac{sV_1^{\frac{1}{\sqrt{2}}}}{R_2'}$$

(1) Induction motor draws a high current at low voltages, which may over heating of the stator winding. For a long period duration of speed control, the heat may damage the stator winding (burning of the winding. That's why this voltage control technique is not suitable for long duration speed control. But it can be applied for short duration speed control.

(2) In this method percentage overloading of stator increases with reduction in speed, that's why this method is not suitable wide range speed of control. But it can be applied for narrow range of speed control.

$$I_1 \propto SV_1$$
$$\frac{I_1''}{I_1'} = \frac{S_2 V_{12}}{S_1 V_{11}}$$

The voltage applied to reduce the full load speed from 100 % to 70 % with constant torque is $\frac{1}{\sqrt{2}}$ time of rated voltage and at the same operating condition slip will become two times of previous slip. Now the current drawn by the motor is:

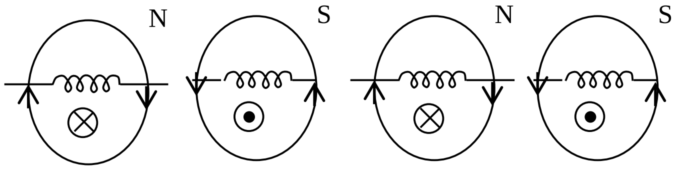
$$I_1 \alpha \frac{SV_1}{R_2^1} \Rightarrow \frac{2 \times \frac{V_1}{\sqrt{2}}}{R_2^1} \Rightarrow \sqrt{2}\left(\frac{SV_1}{R_2^1}\right) \Rightarrow 1.414\ I_1$$

The motor is taking 41.4% extra current from supply mains.

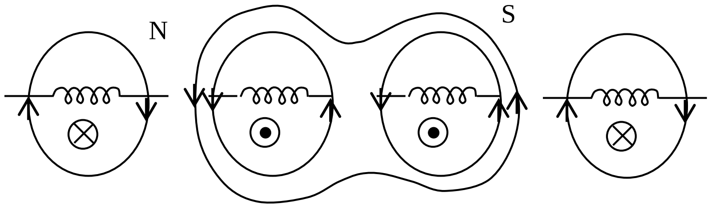
b) Pole changing technique:

This method is easily applicable to squirrel cage induction motors because the squirrel cage rotor adopts itself to any reasonable number of stator pole. This change of number of poles can be achieved by having two or more entirely independent stator windings in the same slots. Each winding gives a different number of poles and hence different synchronous speeds. This method has been used for elevators motors, traction motors and also for small motors driving machine tools. Speeds in the ratio of 2:1 can be produced by a single winding if wound on the consequent pole principle. Here we cannot get variable speeds. We can get only high speed and low speeds only.

$$N_s = \frac{120f}{P}$$



Pole = 4 $\quad N_s = \frac{120 \times 50}{4} = 1500\,\text{rpm} \rightarrow \text{low speed}$



Pole = 2 $\quad N_s = \frac{120 \times 50}{2} = 3000\,\text{rpm} \rightarrow \text{High speed}$

(c) *Frequency control Technique*

Synchronous speed $N_S = \frac{120f}{P}$

The speed N_S will depend on frequency and no. of poles.

By using this frequency control techniques speeds below as well as above rated speeds can be achieved

$V_1 = V_{rated}$(constant) $f < f_{rated}$ *;* It is called pure frequency control technique.

Drawbacks with pure frequency control

(1) To decrease the speed of the induction motor , if the frequency is reduced keeping input voltage constant, air gap flux $\emptyset_R \propto \frac{V_1}{f}$ increases. As $\emptyset_R$ increases so stator core and rotor core goes in to deep saturation as a result core losses increases. So exciting current increases cos $\emptyset_0$ decreases and cos $\emptyset_1$ decreases.

(2) To increase the speed of the induction motor, if the frequency is increased keeping the input voltage constant, air gap flux $\emptyset_R \propto \frac{V_1}{f}$ increases.

$$\downarrow \phi_R \alpha \frac{V_1 = \text{const}}{f \uparrow}$$

$$\Rightarrow I_\mu \downarrow$$

$$\Rightarrow \text{Cos}\phi_0 \text{ and Cos } \phi_1 \uparrow$$

$$T_{max} \alpha \frac{1}{f^2}, \; S_m \alpha \frac{1}{f} \text{ and } T_{St} \alpha \frac{1}{f^3};$$

As frequency increases, T_{max} , S_m and T_{st} will be decreased.

To avoid all these drawbacks $\frac{V_1}{f}$ ratio maintained constant. $\emptyset_R$ is also constant. The corresponding speed control is also called $\frac{V_1}{f}$ control technique

(a) Speed below rated: VVFD (Variable voltage variable frequency drive)

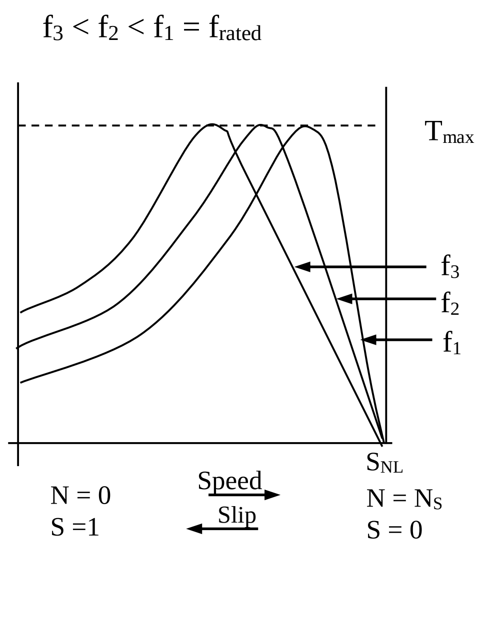
To decrease the speed, below to its rated value the supply frequency is reduced and so as to maintain air gap flux constant (V/f constant), according supply voltage is reduced to maintain the same V/f ratio. This method of control is V/f control method and the drive is variable voltage variable frequency drive.

$\Rightarrow \frac{V}{f} = constant$ and ϕ_R = Constant

$\Rightarrow T_{max}$ = constant and

$S_m \alpha \frac{1}{f}$, $T_{st} \alpha$ 1/f

At steady state $T_{em} = T_L$



If pure frequency control technique is employed to get speeds below the rated value. Following drawbacks takes place

1. $\emptyset_R$ Increases which drives stator and rotor core in too deep saturation.
2. Due to deep saturation of magnetic circuits the machine draws more magnetizing component of current from source.
3. Due to high magnetizing component of current the no load and full load power factors of induction motors will decreases.

Conditions to be satisfied to get constant torque air gap during frequency control technique

$$T \propto \frac{180}{2\pi N_s}\frac{SV_1^2}{R_2}(Approximate\ torque\ equtation)$$

$$T \propto \frac{SV_1^2}{R_2}(constant)$$

$$T \propto \frac{SV_1^2}{N_s} \propto \frac{(N_s - N_r)}{N_s}\frac{V_1^2}{N_s}$$

$$T \propto \left(\frac{V_1}{f}\right)^2 (N_s - N_r)$$

1. $\frac{V_1}{f}$ Ratio should be maintained constant so $\emptyset_R$ is constant. To maintain normal torque.
2. $(N_s - N_r)$ Slip speed should be maintained some for all times.

$$(N_s - N_{r1}) = (N_{s2} - N_{r2}) = (N_{s3} - N_{r3})$$

In order to get constant torque during frequency control technique

1. Air gap flux ($\emptyset_R$) should be maintained constant by keeping $\frac{V_1}{f}$ ratio constant.
2. Slip speed $(N_s - N)$ should be maintained constant

If the above conditions are satisfied the induction motor acts as constant torque variable power drives.

$\therefore$ **The machine acts as constant torque variable power drive by Variable voltage variable frequency device.**

Ex: $\frac{V}{f} = constant$; 400V; 50Hz → N_1 = 950 rpm; for 37.5Hz → N_2 = ?

Sol: $N_{S_1} = \frac{120 \times 50}{6} = 1000 rpm$ $\qquad$ $N_{S_2} = \frac{120 \times 37.5}{6} = 750 rpm$

(1) $\frac{V}{f}$ = const and also slip speed constant

$N_{s1} - Nr_1 = 1000 - 950$ $\qquad$ $N_{s2} - Nr_2 = 50$ rpm

$\Rightarrow 50$ rpm $\qquad$ $\therefore Nr_2 = 700$ rpm

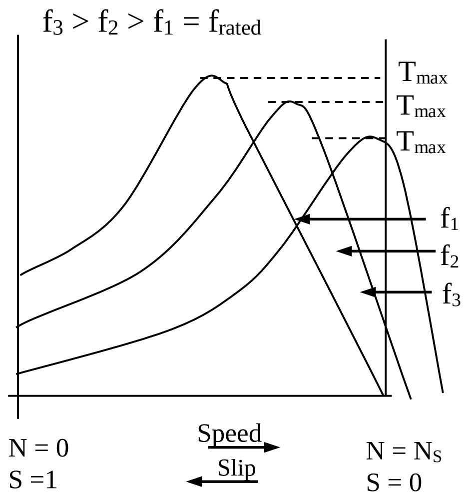
(b) Speeds above rated-Pure frequency control

By keeping the input voltage constant, the supply frequency is increased to increase the speed

- Supply voltage $V_1 = V_{rated}$ and frequency is more than rated frequency.
- Pure frequency control technique by keeping voltage constant. These drivers are variable frequency drives (VFD).
- V/f control technique is not possible for above rated speeds, since voltage can't be increase beyond rated value.
- $\downarrow \phi_R \alpha \dfrac{V_1 = const}{f \uparrow}$

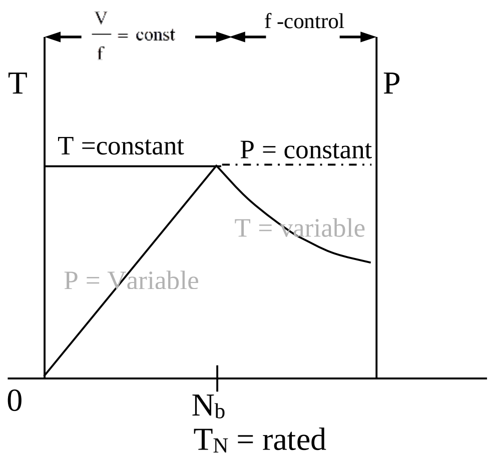
  $\Rightarrow I_\mu \downarrow$

  $\Rightarrow Cos\phi_0$ and $Cos\ \phi_1 \uparrow$
- $T_{max} \alpha \dfrac{1}{f^2}$, $S_m \alpha \dfrac{1}{f}$ and $T_{St} \alpha \dfrac{1}{f^3}$; As frequency increases, T_{max}, S_m and T_{st} will be decreased.
- These motors comes into the category of constant Power variable torque motors.



(c) Combination of VFD and VVFD graph

Ward Leonard method control of D.C machine characteristics are same as speed control of Induction motor characteristics by controlling VFD, VVVFD.



(u) Rotor resistance method of speed control:

Insert some external resistance (R_e) in series with rotor winding (in slip ring induction motor) under load condition.

$$T \propto \frac{sV_1^2}{R_2 + R_e}$$

Here voltage kept constant. To maintain load torque is constant so that slip increases.
In this method some external resistance is to be inserted in series with wound rotor under load condition to reduce speed.
But if external resistance is inserted under load condition the slip of induction motor increases to maintain the load torque constant. There by reduces the speed of induction motor below its rated value.
By using method also speeds below the rated value can be achieved.
During this speed control technique also inductive motor acts as constant torque variable power drive.

$$T = constant$$

$$\frac{S_1}{R_2} = \frac{S_2}{R_2 + R_e}$$

To maintain load torque constant

Drawbacks of rotor resistance method of speed control

1. Due to the presence of additional copper losses in the external resistance (R_e). The efficiency of induction motor decreases during this speed control.
2. Due to excessive over heating of external resistance this speed control is not suitable for long duration speed control but it can be applied for short duration speed control.
3. In this method efficiency of induction motor decreases with reduction method. That's why this method is not economical for wide range of speed control. But it can be employed for narrow range of speed control

A 6-pole, 50Hz induction motor is operating with rotor resistance R_2 = 0.2Ω/ph and speed N_1 = 950 rpm, now the motor has to operate at speed N_2 = 800 rpm then find the value of inserted resistance in the rotor when load torque is constant.

Sol: From given data N_S = 1000r.p.m

$$S_1 = \frac{1000-950}{1000} = 0.05, \; S_2 = \frac{1000-800}{1000} = 0.2$$

$$\frac{S_1}{R_2} = \frac{S_2}{R_2 + R_e} \Rightarrow \frac{0.05}{0.2} = \frac{0.2}{0.2 + Re} \Rightarrow R_e = 0.6\Omega/ph$$

(v) Rotor EMF injection method

Case 1: If an emf is injected in phase with the existing rotor emf

$sE_{20} = I_2Z_2$ with rotor winding short circuit

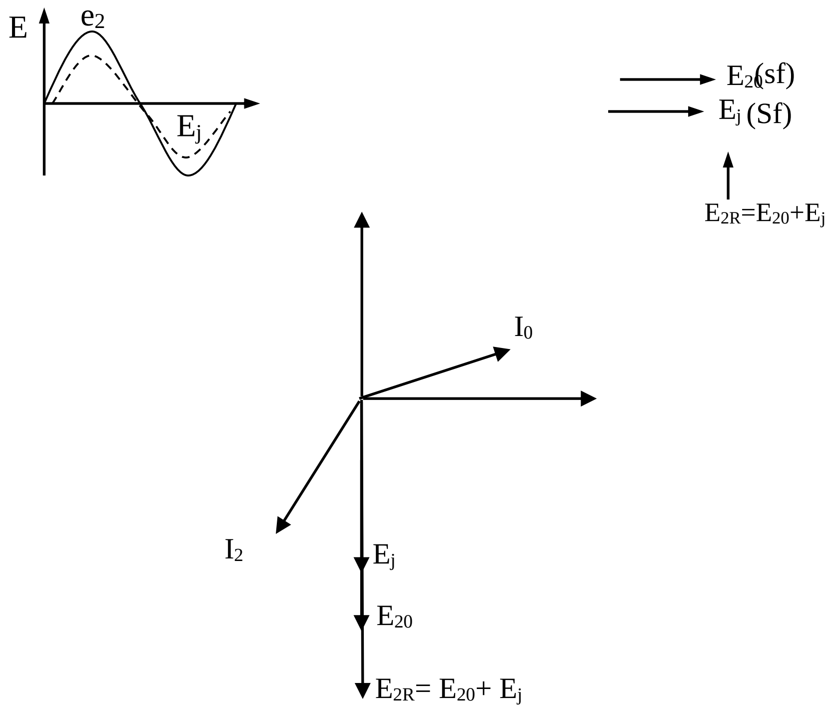
Let E_j be the emf/phase in the rotor circuit

$$sE_{20} + E_j = I_2Z_2$$

$$sE_{20} = -E_j + I_2Z_2$$

$$s = \frac{-E_j}{E_{20}} + \frac{I_2 Z_2}{E_{20}}$$

If $\frac{I_2 Z_2}{E_{20}}$ is neglected then the new slip is $= \frac{-E_j}{E_{20}}$; slip is negative, and we can get the speeds greater than synchronous speeds, $N_r = N_s(1+s)$



Case 2: If an emf is injected in phase opposition with the existing rotor emf

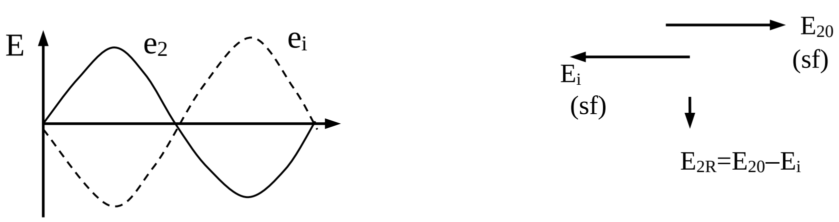
$\mathrm{sE}_{20} = \mathrm{I}_2\mathrm{Z}_2$ with rotor winding short circuit

Let E_j be the emf/phase in the rotor circuit

$$\mathrm{sE}_{20} - E_j = \mathrm{I}_2\mathrm{Z}_2$$

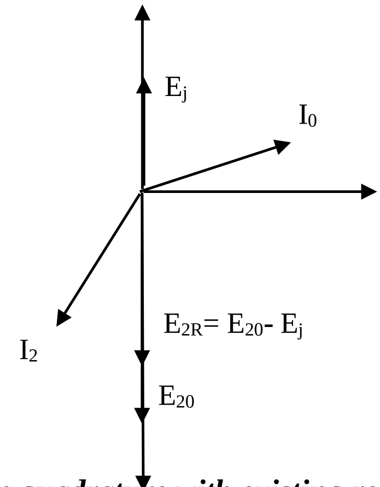
$$sE_{20} = +E_j + I_2 Z_2$$

$$s = \frac{+E_j}{E_{20}} + \frac{I_2 Z_2}{E_{20}}$$

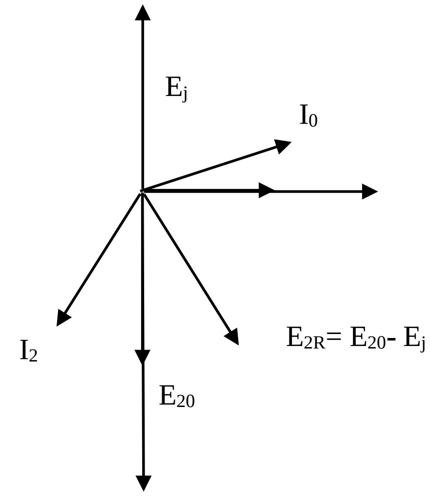


E_{2R} = Resultant e.m.f in the rotor.

If $\frac{I_2 Z_2}{E_{20}}$ is neglected then the new slip is $= \frac{E_j}{E_{20}}$; slip is positive, and we can get the speeds below synchronous speeds, $N_r = N_s(1-s)$



Case 3: If an emf is injected in quadrature with existing rotor emf

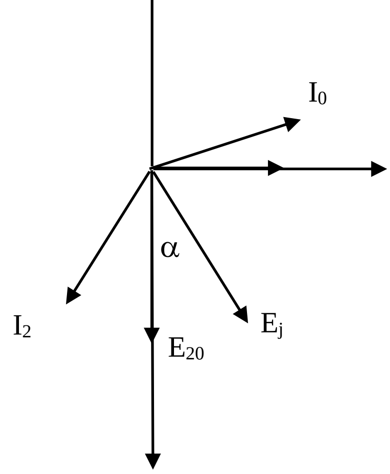


Let E_j be the emf/phase in the rotor circuit

$$sE_{20} + jE_j = I_2Z_2$$
$$sE_{20} = -jE_j + I_2Z_2$$
$$s = \frac{-jE_j}{E_{20}} + \frac{I_2Z_2}{E_{20}}$$

If an emf at slip frequency is injected in quadrature with the existing rotor induced emf, the power factor of the motor can be improved

Case 4: If an emf is injected at an angle α with existing rotor emf



If an emf at slip frequency is injected at angle α with the existing rotor induced emf, the power factor of the motor can be improved and speed changes

Ex: If the rotor emf E_2 = 200V and rotor speed is 950 rpm , now the injected emf is 20V out of phase with E_2 then find motor speed when load torque is constant. Take N_S = 1000 rpm.

Sol: $s_1 = 0.05$

$0.05(200)^2 = s_2\,(200-20)^2$

$\Rightarrow s_2 = 0.06$

$N_{r2} = N_S\,(1-s_2)$

N_{r2} = 940 rpm (Below rated speed)

If injected voltage is in-phase

$0.05(200)^2 = s_2\,(200 + 20)^2$

$\Rightarrow s_2 = 0.04$

$N_{r2} = N_S\,(1-S_2)$

N_{r2} = 960 rpm (Above rated speed)

A 3-phase 400V, 50 Hz, 4 pole slip ring induction motor has a voltage of 100 volts between any slips at stand still. What will be the steady state speed of the motor, if an emf of 20 volts is injected in phase and in phase opposition*? *Ans: 1800 rpm and 1200 rpm

A 50Hz, 3-phase wound-rotor induction motor is running with a slip of 0.03. The per phase rotor e.m.f and leakage impedance at standstill are 200V and 0.3+j 0 Ω respectively. For obtaining slips of 0.4, 0 and -0.4, calculate the magnitude, frequency and phase of the injected voltage in the rotor circuit, when the load torque is constant

Sol:

Electromagnetic torque, $T_e \propto E_2 I_2 \cos\theta_2$

Since rotor circuit is purely resistive, $\cos\theta_2 = 1$

$$\therefore\ T_e \propto E_2 I_2$$

The standstill rotor voltage E_2 remains substantially constant; in view of this $T_e \propto I_2$

For torque balance, $T_e = T_L$

So load torque $\propto I_2$

The rotor current I_2 remains constant for all the rotor speeds at constant torque load.

Under normal operation and with the rotor short-circuited

$$I_2 r_2 = sE_2$$

$$I_2 = \frac{sE_2}{r_2} = \frac{(0.03)(200)}{0.3}$$

$$= 20\ A.$$

Voltage equation for the rotor circuit is

$$\overline{I_2}\overline{r_2} = s\overline{E_2} + \overline{E_J}$$

For slip s=0.4

$$(20)(0.3) = (0.4)(200) + \overline{E_J}$$

$$\overline{E_J} = -74\,V.$$

Since E_j is negative, 74 volts at a frequency of 20Hz must be injected in phase opposition to E_2. The same conclusion can be arrived at from physical considerations. For obtaining larger slips, or speeds less than the normal one, the injected voltage should be in phase opposition to the rotor voltage E_2.

For slip s= 0, $(20)(0.3) = 0 + \overline{E_J}$

$$\overline{E_J} = 6V$$

Since E_j is positive the injected voltage at frequency should be in phase with E_2.

For slip s= -0.4, $\overline{E_J} + (-0.4)(200) = (20)(0.3)$

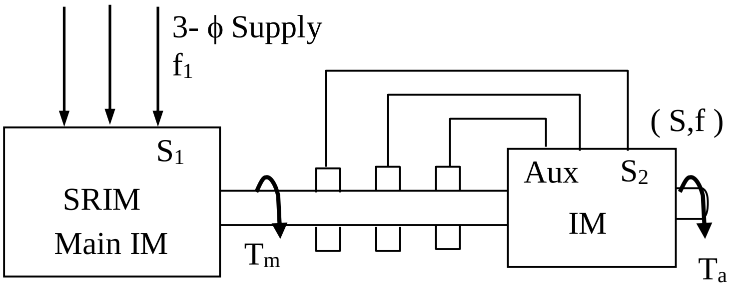
$$\overline{E_J} = 86V$$

Here $\overline{E_J}$ is positive, therefore, 86V at a frequency of 20Hz must be in phase with E_2.

(w) Cascading of two induction motors

Condition:

1. One induction motor must be slip ring induction motor P_1
2. $P_1 \neq P_2$



Case 1:

If the excitation is given to main induction motor with auxiliary induction motor left unexcited

$$N_{set} \cong \frac{120f}{P_1}$$

Case 2:

If the excitation is given to main induction motor with auxiliary induction motor left unexcited

$$N_{set} \cong \frac{120f}{P_1}$$

Case 3

Two types of cascading

This technique is Slip power recovery speed control technique

(i) Cumulative cascading

(ii) Differential cascading

Cumulative cascading:

(i) Two induction motors said to be cumulative cascaded with the torque produced by them acting same direction.

(ii) In order to get cumulative effect the phase sequence allotted both induction motors should be same.

Differential cascading:

(i) The induction motors are said to be differentially cascaded if the torque produced by them acting opposite direction.

(ii) In order to get differential effect the phase sequence adopted at any one of the induction motor should be reversed **cumulative cascading**

Cumulative Cascade

$$N_m = \frac{120f}{P_1}(1 - s_1)$$
$$N_a = \frac{120(s_1 f)}{P_2}(1 - s_2)$$

In cumulative cascading N_m=N_a

In differential cascading N_m=$-N_a$

For cumulative cascading

$$\frac{120f}{P_1}(1 - s_1) = \frac{120(s_1 f)}{P_2}(1 - s_2)$$
$$s_1 = \frac{P_2}{P_2 + P_1 - P_1 s_2}$$
$$s_1 \cong \frac{P_2}{P_2 + P_1}$$

s_1 is the slip of main induction motor corresponding to set speed with cumulative cascading.

$$N_{set} = \frac{120f}{P_1}\left(1 - \frac{P_2}{P_2 + P_1}\right) = \frac{120f}{P_2 + P_1}$$

Here we get low speed operation

Differential cascading:

$N_m = -N_a$ (Torque are opposite)

$$S_1 = \frac{P_2}{P_2 - P_1 + P_1 S_2} \quad (P_1 S_2 \ is \ neglected)$$

s_1 is the slip of main induction motor corresponding to set speed with differential cascading.

$$N_{set} = \frac{120f}{P_2 - P_1}$$
$$N_{set} = \frac{120f}{P_2 \pm P_1}$$

+ Cumulative cascading

- Differential cascading

Power flow in cascade connection set

P_{GM}=electrical input to cascade connection, input to the main induction motor

Gross mechanical power output in main induction motor=$(1 - s_1)P_{GM}$

Electrical power recovered rotor MIM=$s_1\ P_{GM}$
Electrical power input to auxiliary induction motor =$s_1\ P_{GM}$
Mechanical power output in MIM: Electrical recovered from MIM

$$(1 - S_1)P_{GM}: S_1 P_{GM}$$
$$(1 - S_1): S_1$$
$$\left(1 - \frac{P_2}{P_2 + P_1}\right): \frac{P_2}{P_2 + P_1}$$
$$P_1: P_2$$

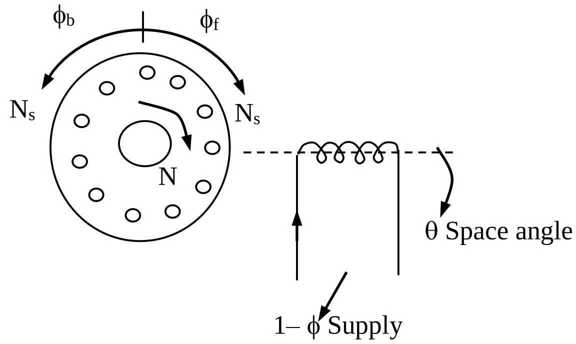
Gross mechanical power output of MIM: $P_{GM}\,\frac{P_1}{P_2+P_1}$

Electrical power from rotor of MIM: $P_{GM}\,\frac{P_2}{P_2+P_1}$

What are the synchronous speeds possible with two electrically and mechanically coupled induction motors with 6-pole and 8-pole respectively and running on 50 Hz supply.
Ans:429 rpm, 3000 rpm, 750 rpm and 1000 rpm.

These are small rating induction motors, so these are called fractional KW induction motors. These are used for domestic purpose.

First consider a single phase, single winding induction motor
Here only one single winding is present



If N$cos\,\emptyset$; no. of turns which are placed at an space angle θ *and* i(t)=$i_m\ cos\,\omega t$
By applying double field theory.
The $1-\emptyset$ MMF can be divided two oppositely rotating MMF waves which rotate at synchronous speeds in opposite directions.

$$F = F_m\, cos\,\theta\, cos\,\omega t$$
$$= \frac{F_m}{2} cos(\theta - \omega t) + \frac{F_m}{2} cos(\theta + \omega t)$$
$$= F_f \quad + \quad F_b$$
$$\downarrow \qquad \downarrow$$
$$\phi_f \qquad \phi_b$$
$$cos(\theta + \omega t) - backward\ rotating$$
$$cos(\theta - \omega t) - forward\ rotating$$
$$= F_f + F_b$$

Both of these magnetic fields rotate with synchronous speed. Because of two fluxes, here two slips are present

Forward slip $s_f = \frac{N_s - N}{N_s} = s$

Backward slip $s_b = \frac{N_s - (N) + N_s - N_s}{N_s}$ = 2-s

Therefore backward slip = 2-s*;* Slip can be defined with the direction of rotation of rotor.

- (2 – s) > > s and $s_b >> s_f$
- Slip changes with direction of rotation of rotor. If rotor rotates in anticlockwise direction then $s_f = 2 - s$, and $s_b = s$.
- At stand still, $N_r = 0$, $s_f = 1$ and $s_b = 1$.

ϕ_f	ϕ_b
(Main field forward flux)	**(Main field backward flux.)**
↓	↓
E_{2f}	E_{2b}
↓	↓
I_{2f}	I_{2b}

Two currents are produced in rotor. The direction of these currents can be found by lenz's law and these currents produce forward flux and backward flux

ϕ_{2f} and ϕ_{2b}.

ϕ_{2f} should oppose ϕ_f and ϕ_{2b} should oppose ϕ_b

$\downarrow$ $\downarrow$

ϕ_{rf} ϕ_{rb}

$\downarrow$ $\downarrow$

Therefore the resultant fluxes are

ϕ_{rf} = Resultant forward flux = $\phi_f - \phi_{2f}$

ϕ_{rb} = Resultant backward flux = $\phi_b - \phi_{2b}$

$\downarrow$ $\downarrow$

T_f T_b

$T_f \propto \frac{1}{s_f} \propto \frac{1}{s}$ $T_b \propto \frac{1}{s_b} \propto \frac{1}{2-s}$

At the time starting N_r=0; initially rotor it is at rest:

Forward slip $S_f = 1$; backward slip $S_b = 2 - 1 = 1$

Forward speed =N_s; Backward speed =N_s

In rotor two rotor currents are flowing through rotor bars. Direction of rotor current found by LENZ's law.

$$\emptyset_{2f} - flux\ due\ to\ rotor\ winding$$

The direction of I_{2f} found by applying the LENZ's law

Resulting forward flux $\emptyset_{rf} = \emptyset_f - \emptyset_{2f}$

Resultant backward flux $\emptyset_{rb} = \emptyset_b - \emptyset_{2b}$

Both torques are operating in opposite direction.

$$T_r = T_f \sim T_b$$
$$T_r = 0$$

That's why we can say that $1-\emptyset$, single winding it cannot produce starting torque at the time of starting

Note:

(1) $1-\emptyset$ single winding induction motor is not a self -starting one, due to presence of equal strength of resultant forward and backward fluxes at the time of starting. As starting torque is zero rotor cannot accelerate

Rotor under running condition:

Once motor is in running condition slips are not equal

$$F_f \neq F_b$$
$$\emptyset_{rf} = \emptyset_f - \emptyset_{2f}$$
$$\emptyset_{rb} = \emptyset_b - \emptyset_{2b}$$
$$\emptyset_{rf} > \emptyset_{rb}$$
$$T_f > T_b$$

$T_r = T_f - T_b \neq 0$

So to make 1 - ϕ IM, self-starting we should weaken one field and simultaneously strengthening another field at the time of starting. So for this purpose wound another winding in the induction motor this is called Auxiliary winding for starting purpose.
This type of induction motor can produce torque under running condition due to presence of unequal strengths of resultant forward and backward fluxes under running condition. In order to make the induction motor self-starting the resultant forward and backward field should be made unequal at the time of starting by using some arrangement

Starting Methods

(i) Small pony motors

(ii) Auxiliary windings

Small pony motors:

Initially the induction motor rotor is coupled with a pony motor and started , and as it reaches to running condition the pony motor is separated and the induction motor operates at own speed.

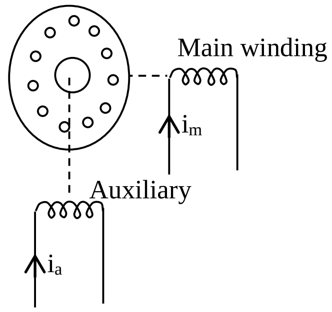
Auxiliary winding:

Auxiliary winding is required only for starting purpose

☞ Condition to be satisfied in case of Auxiliary winding:

(1) Auxiliary winding must be placed at 90° electrical to the main field winding. That is they are physically displaced by 90° electrical.

(2) The current flowing through those windings must have some phase displacement. If angle between main & auxiliary winding current is zero, then no torque is produce.



Main winding:

F_{fm} $\qquad$ F_{bm}

$\downarrow$ $\qquad$ $\downarrow$

$\emptyset_{fm} \rightarrow$ $\qquad$ $\leftarrow \emptyset_{bm}$

Auxiliary windings:

$$N\,cos(\theta - 90)$$
$$I_a = I_m\,cos(\omega t - 90)$$
$$F_a = N\,cos(\theta - 90)\,I_m\,cos(\omega t - 90)$$
$$F_a = F_m cos(\theta - 90)\,cos(\omega t - 90)$$

If we apply double field revolving theory of F_a

$$F_a = \frac{F_m}{2} cos(\theta - \omega t) + \frac{F_m}{2} cos(\theta + \omega t - 180°)$$
$$= F_{fa} + F_{ba}$$

$\emptyset_{fm}$& $\emptyset_{fa}$ both are in same phase

$$F_{bm} = \frac{F_m}{2} cos(\theta + \omega t°)$$

They are called in space phase with each other.

$$F_{RF} = F_{fm} + F_{ba}$$

$$F_{Rb} = F_{bm} - F_{ba}$$
$$F_{RF} > F_{Rb}$$
$$\emptyset_{rf} > \emptyset_{rb}$$
$$T_f > T_b$$
$$T_{RST} = T_f - T_b$$

By changing reversing auxiliary winding terminals:

$$F_{RF} < F_{Rb}$$
$$\emptyset_{rf} < \emptyset_{rb}$$
$$T_f < T_b$$
$$T_{RST} = T_b - T_f$$

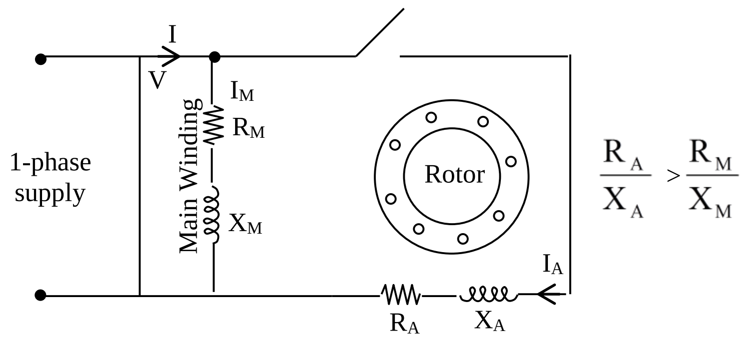
Rotor rotates at backward position. By reversing main winding terminals the direction is reversed not by both.

The direction of rotation of $1-\emptyset$ Two winding induction motor can be reversed by reversing either main winding terminals o auxiliary winding terminals. In order to get time displacement between currents in the main winding and auxiliary winding split phase technique should be employed

In order to get time phase displacement between field and auxiliary winding currents, use split phase techniques.

(1) Resistance split phase induction motor.
(2) Capacitance split phase induction motor.

(a) SPLIT PHASE INDUCTION MOTOR

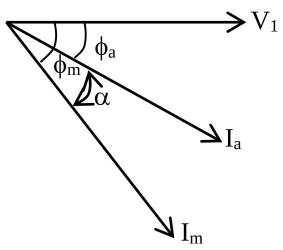


Stating (Auxiliary winding)

Split phase induction motor connections.

1 The split phase induction motor is also called as resistance start motor.
2 It is a single cage rotor and its stator has two windings a main winding and a starting winding.
3. The main field winding and starting winding are displaced 90^0 in space like the windings in a 2-phase induction motor.
4. The main winding has very low resistance and high inductive reactance.
5. The current I_M in the main winding lags behind the supply voltage by nearly 90^0.
6. The auxiliary winding has a resistor connected in series with it. It has a high resistance and low inductive reactance so that the current I_A in the auxiliary winding is nearly in phase with the line voltage.

7. Thus there is a time difference between the currents in the two windings and it is of order 30^0. This phase difference is enough to produces a rotating magnetic field.
8. Since the currents in the two windings are not equal, the rotating field is not uniform, and the starting torque is small of order of 1.5 to 2 times the rated running torque.
9. The main and auxiliary winding are connected parallel in during starting.
10. The starting winding is automatically disconnected from the supply when motor reaches speed about 70 to 80 percent of synchronous speed.
11. For motor rated about 100W or more, a centrifugally operated switch is used to disconnect the starting winding.
12. For smaller motors a relay is often used. The relay is connected in series with the main winding.
13. At the time of starting, a heavy current flows in the relay coil causing its contact to lose. This brings starting winding into the circuit.
14. As the motor reaches its predetermined speed of the order of 70 to 80 per cent of synchronous speed, the current through the relay coil decreases as consequently, the relay opens and disconnects the auxiliary winding from the main supply and the motor there runs only on the main windings.
16. The torque speed characteristics of this motor is also shows speed n_0 at which centrifugal operates.



$$\frac{X_m}{R_m} > \frac{X_a}{R_a}$$

$$\phi_m = \tan^{-1}\left(\frac{X_m}{R_m}\right) \quad ; \quad \phi_a = \tan^{-1}\left(\frac{X_a}{R_a}\right)$$

$\phi_m > \phi_a$

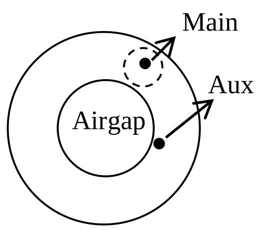
$\therefore\ T_{st}\ \alpha\ I_m\ I_a \sin \alpha$

☞ To get $\frac{X_m}{R_m} > \frac{X_a}{R_a}$

- Main winding is to be made with thick wire so as to get less R_m.
- Auxiliary winding is to be made with thin wire so as to get more R_a.

☞ Main winding is placed away from air gap.

☞ Auxiliary winding is placed nearer to the air gap.



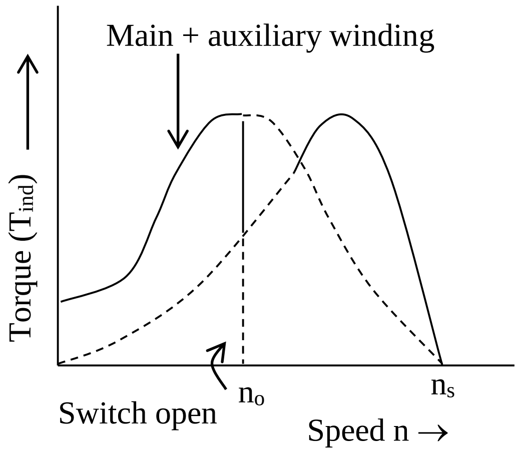
We know that $T_{st}\ \alpha\ I_m I_a \sin \alpha$

If $\alpha = 90°$; T_{st} is maximum.

So to get $T_{stmax} \Rightarrow \phi_m \sim \phi_a = 90°$.

$$\Rightarrow \mathrm{Tan}^{-1}\left(\frac{X_m}{R_m}\right) - \mathrm{Tan}^{-1}\left(\frac{X_a}{R_a + R_e}\right) = 90^0$$

From this equation R_e will be obtained at which maximum T_{st} is occurring i.e to get T_{st} maximum, what value of resistance is to be placed in Auxiliary winding is found. But practically very large amount of resistance is to be added and is very difficult so we go for capacitance split phase technique.



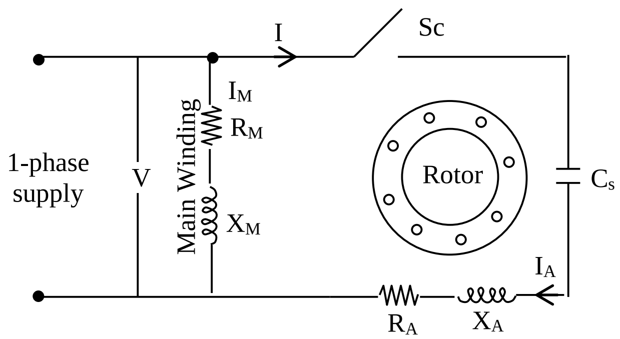
Torque – speed characteristics

APPLICATIONS:

1. Split phase motors are cheap and they are most suitable for easily started loads where frequency of starting is limited.
2. The common applications are washing machines, air conditioning fans, food miners, grinders, centrifugal pumps, floor polishers, blowers, small drills, office machinery, dairy machinery etc.
3. Because of low starting torques, they are set down used for drives requiring more than 1KW.

CAPCITOR – START MOTOR:

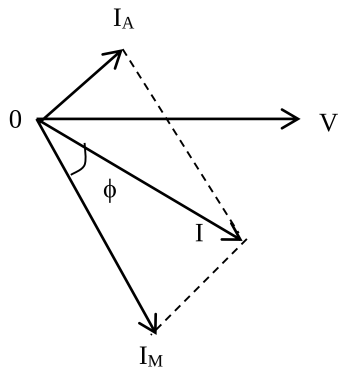
Circuit diagram of capacitor start motor



1. It has a cage rotor and its stator has two windings namely, the main winding and the auxiliary winding.

2. The two windings are displaced 90^0 in space. A centrifugal switch is connected and a capacitor c_s is connected in series with starting windings.
3. By choosing a capacitor of the proper rating the current I_M in the main winding may be made to lag the current I_A in the auxiliary winding by 90^0.
4. Thus a single phase supply current is split into two phases to be applied to the stator windings.
5. Thus the windings are displaced 90^0 electrical and their mmf's are equal in magnitude but 90^0 apart in time phase
6. The motor acts like a balanced two-phase motor.
7. As the motor approaches its rated speed, the auxiliary winding and the starting capacitor c_s are disconnected automatically by the centrifugal switch s_c mounted on the shaft
8. The motor is named because it uses the capacitor only for the purpose of starting.

Phasor diagram:



To get maximum starting torque, what is the value of capacitance of the capacitor?

Maximum T_{st} can be obtained when $\phi_m + \phi_a = 90°$

$$Tan^{-1}\left(\frac{X_m}{R_m}\right)+Tan^{-1}\left(\frac{X_a - X_c}{R_a}\right)=90^o$$

From this equation we find X_c and then $C=\dfrac{1}{2\pi f x_c}$ is found.

Requirements of starting capacitor

1. High capacitance, $C_s \cong 250\ \mu F$
2. High VAR rating
3. Mica – capacitor
4. Short duration rating
5. Specified with V_{peak}

Draw backs:

Capacitor start induction motor has good starting condition but poor running conditions, because capacitor is disconnected in running conditions. So only main field winding is connected to Induction motor under running condition.

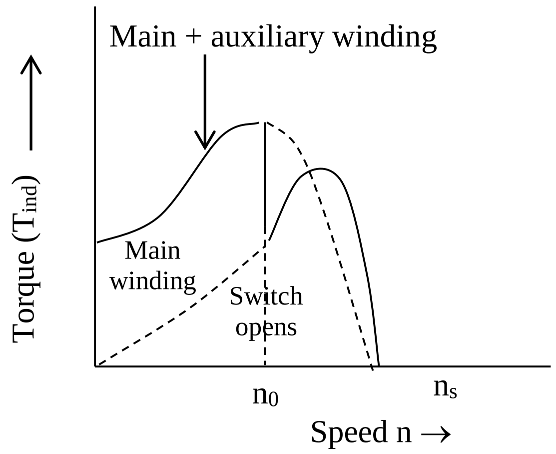
The produced fluxes are.

$$\begin{array}{ll} \phi_{rf} > & \phi_{rb} \\ \downarrow & \downarrow \\ T_F & T_b \Rightarrow T_R = T_F - T_b. \end{array}$$

Resultant torque is reduced due to presence of resultant backward flux of main field winding.

- ❖ Efficiency and power factors are poor.
- ❖ Good starting performance, inferior running performance

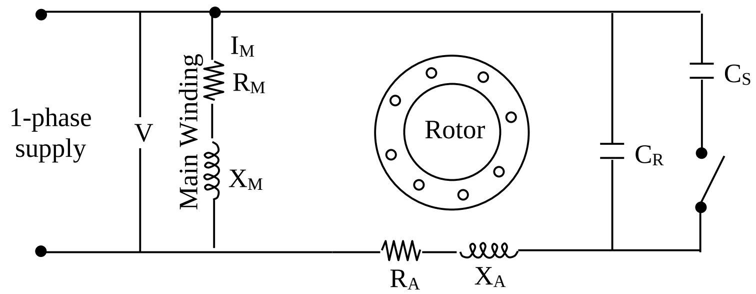
Torque-speed characteristics:



APPLICATIONS OF CAPACITOR – START MOTOR:

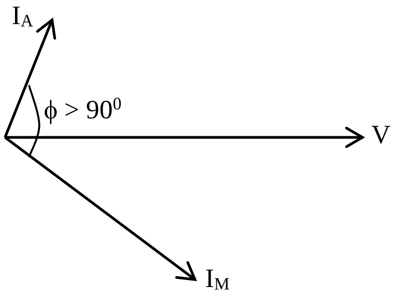
1 Capacitor start motors are used for loads of higher where frequent starts are required.
2. There motors are most suitable for pumps and compressor and therefore they are widely used in refrigerators and in air-conditioner compressors.
3. They are also used for conveyors and some machine tools.

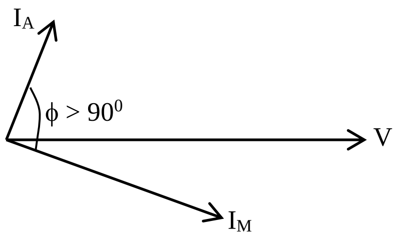
TWO VALUE CAPACITOR MOTOR:



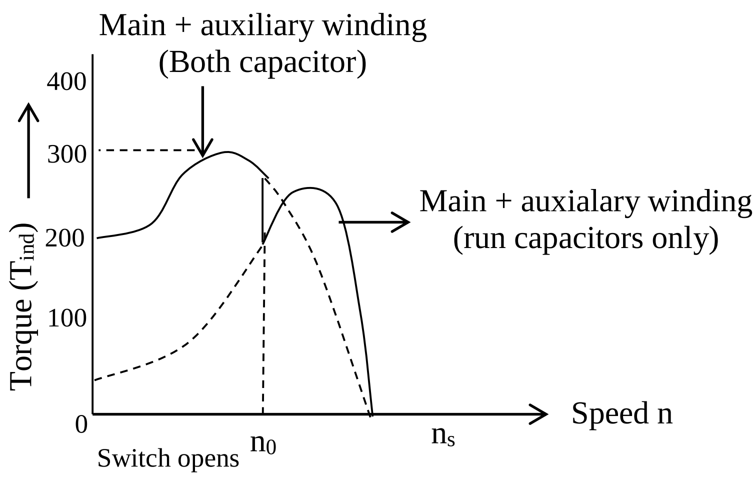
1. The two value capacitor motor has a cage rotor and its stator has two windings namely the main winding and the auxiliary winding.
2. The two windings are displaced 90^0 in space.
3. The motor uses two capacitors C_S and C_R. The two capacitors are connected in parallel at starting.
4. The capacitor C_S is called the starting capacitor. In order to obtain a high starting torque a large current is required.
5. For this purpose the capacitive reactance 'X_0' the starting winding should be low.
6. Since X_A = ½(2πfc_A), the value of C_S should be large. The capacitor C_s is short – time rated is almost always electrolytic.

7. During normal operation, the rated line current is smaller than the starting current.
8. Hence the capacitive reactance should be large. Since the $X_R = 1|(2\pi f(\quad R)$, the value of C_R should be small.
9. As the motor approaches synchronous speed, the capacitor "C_S" is disconnected by a centrifugal switch "S_C"
10 The capacitor C_R is permanently connected in the circuit, it is called the run-capacitor. It is long time rated for continuous running. It is usually of oil filled paper construction.
11. Since one capacitor C_s is used only at starting and the other C_R for continuous running, this motor is called capacitor – start capacitor – run motor.





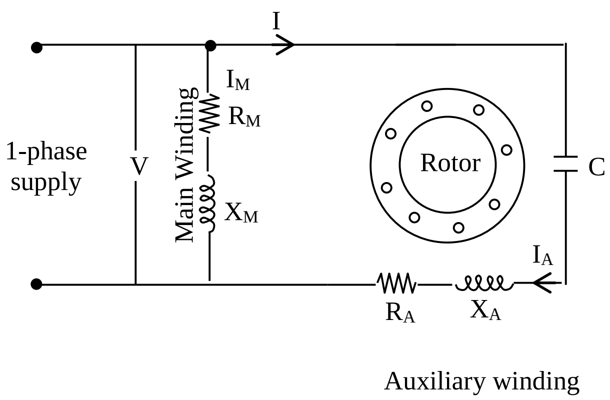
Torque- speed characteristics:



APPLICATIONS:

1 Two value capacitor motors are used for loads of higher inertia requiring frequency starts where the maximum pull out torque and efficiency required are higher.
2. They are used in pumping equipment, refrigeration air compressors etc.

PERMANENT SPLIT CAPACITOR (PSC) MOTOR



1. It has cage rotor and its stator has two windings namely main winding and auxiliary winding.
2. This single phase induction motor has only one capacitor C which is connected in series with the starting winding.
3. The capacitor C is permanently connected in series with the circuit both at starting and running conditions.
4. A permanent split capacitor motor is also called the single-value capacitor motors.
5. Since the capacitor C is always in the circuit this type of motor has no starting switch.
6. The auxiliary winding is always in the circuit, and therefore this motor operates in the same way as a balanced two – phase motor.
7. Consequently, it produces a uniform torque. The motor is therefore less noisy during operations.

ADVANTAGES:

A single-value capacitor motor possess the following advantages.

1 No centrifugal switch is required
2. It has higher efficiency
3. It has higher power factor because of permanently connected capacitor
4. it has a higher pull-out torque

LIMITATIONS:

1. Electrolytic capacitors cannot be used for continuous running. Therefore paper-spaced oil-filled type capacitors are to be used. Paper capacitors of equivalent rating are larger in size and more costly.
2. A single – value capacitor has a low starting torque usually less than full-load torque.

❖ **The Capacitors**

The start capacitor used in the **capacitor start capacitor run motor** is a large electrolytic type designed for use on AC but is intermittently rated. Depending on the power rating of the motor its value will be between 20 μF and 300 μF. It will have a working voltage of approximately 275 Volts.

The run capacitor used in the **capacitor start capacitor run motor** is a polypropylene type and is continuously rated. Depending on the power rating of the motor its value will be between 1μF and 30 μF. It will have a working voltage of approximately 400 Volts

T_{st} (Capacitor start induction motor)	>	T_{st} (Two value capacitor Induction motor)	>	T_{st} (Capacitor RUN Induction motor)	>	T_{st} (Resistance split phase)

T_{st} (Two value Capacitor IM)	=	T_{st} (Capacitor run IM)	>	T_{st} (Resistance Split Phase)	>	T_{st} (Capacitor start induction

The main & Auxiliary winding impedances of 50Hz, capacitor – start 1ϕ induction motor are..,

Main winding $\overline{Z}_{1m} = 3 + j2.7$

Auxiliary winding $\overline{Z}_{1m} = 7 + 3j$

Determine the value of the capacitor to the connected in series with the auxiliary winding to achieve a phase difference of $\alpha = 90^0$ between the currents of two windings at start.

Sol: Phase angle of Main winding current

$$\angle\overline{I}_m = -\angle\overline{Z}_{1m} = -\angle(3 + j2.7) = -42^0$$

The phase angle of auxiliary winding current with capacitor in series

$$\angle\overline{I}_a - \angle[(t + j3) - j/w_c]$$

$$\alpha = \angle\overline{I}_a - \angle\overline{I}_m$$

$$90^0 = -\tan^{-1}\left[\frac{3 - 1/w_c}{7}\right] - (-42^0)$$

(or)

$$\tan^{-1}\left(\frac{3 - 1/w_c}{7}\right) = -48^0$$

$$\frac{3\left(\frac{1}{wc}\right)}{7} = -1.11$$

W = 2π×50 rad/sec

C = 295.5μF

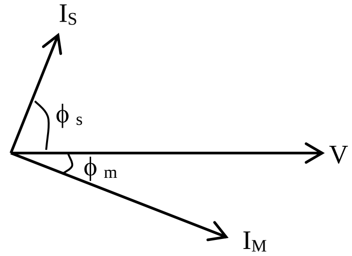
A 200W, 230V, 50Hz capacitor – start motor has the following constants

Main winding: R = 4.5Ω, X_L = 3.7Ω

Starting winding: R = 9.5 x_{2l} = 3.5Ω

Find the value of starting capacitance that will result in maximum starting torque.

Sol: The current 'I_s' in the starting winding leads the applied voltage 'V' by ϕ_S, While the current 'I_m' in main winding lags V by ϕ_m. The starting torque will be max when phase angle & between I_s & I_m is 90^0.



$$\phi_m = \tan^{-1}\left(\frac{3.7}{4.5}\right) = 39.6^0$$

$\phi_S = 39.6 – 90^0 = –50.4^0$

Let ‘C’ farad be the capacitance of starting capacitor to give starting torque

$$\tan\left(-50.4^0\right) = \frac{3.5 - X_C}{9.5} \quad \Rightarrow X_C = 15\Omega$$

$$C = \frac{1}{2\pi F x_C}$$

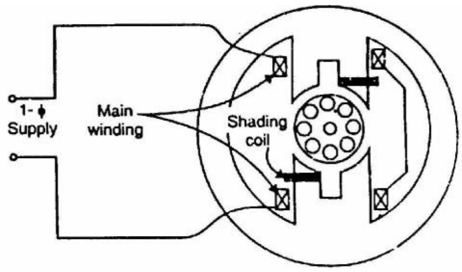
$$= \frac{1}{2\pi \times 50 \times 15}$$

$= c = 212\mu F$

Shaded-Pole Motor

The shaded-pole motor is very popular for ratings below 0.05 H.P. (~ 40 W) because of its extremely simple construction. It has salient poles on the stator excited by single-phase supply and a squirrel cage rotor as shown in Figure

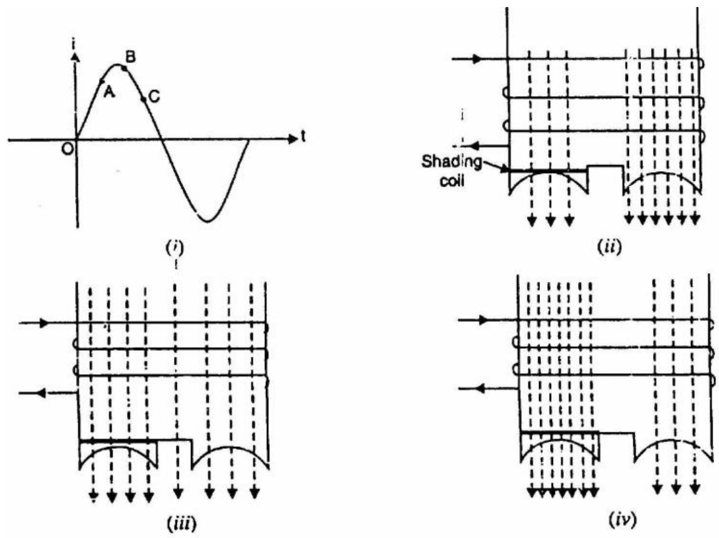
A portion of each pole is surrounded by a short-circuited turn of copper strip called shading coil.



Operation

The operation of the motor can be understood by referring to Figure shown which shows one pole of the motor with a shading coil. (i) During the portion OA of the alternating-current cycle [See Figure} the flux begins to increase and an e.m.f. is induced in the shading coil. The resulting current in the shading coil will be in such a direction (Lenz’s law) so as to oppose the change in flux. Thus the flux in the shaded portion of the pole is weakened while that in the unshaded portion is strengthened as shown in Fig. (ii).

(ii) During the portion AB of the alternating-current cycle, the flux has reached almost maximum value and is not changing. Consequently, the flux distribution across the pole is uniform [See Fig. (iii)] since no current is flowing in the shading coil. As the flux decreases (portion BC of the alternating current cycle), current is induced in the shading coil so as to oppose the decrease in current. Thus the flux in the shaded portion of the pole is strengthened while that in the unshaded portion is weakened as shown in Fig. (iv).



(iii) The effect of the shading coil is to cause the field flux to shift across the pole face from the unshaded to the shaded portion. This shifting flux is like a rotating weak field moving in the direction from unshaded portion to the shaded portion of the pole.

(iv) The rotor is of the squirrel-cage type and is under the influence of this moving field. Consequently, a small starting torque is developed. As soon as this torque starts to revolve the rotor, additional torque is produced by single-phase induction-motor action. The motor accelerates to a speed slightly below the synchronous speed and runs as a single-phase induction motor.

Characteristics

(i) The salient features of this motor are extremely simple construction and absence of centrifugal switch.

(ii) Since starting torque, efficiency and power factor are very low, these motors are only suitable for low power applications e.g., to drive: (a) small fans (6) toys (c) hair driers (d) desk fans etc.

The power rating of such motors is upto about 30 W.

Deep bar and Double cage rotors:

(1) Deep bar rotor:

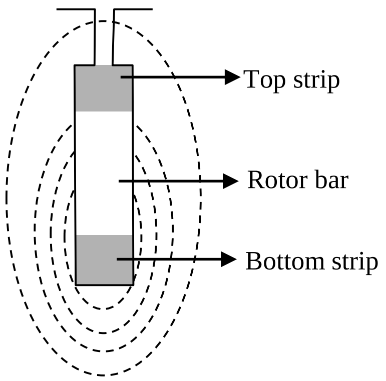


Fig: rotor bar with leakage flux pattern

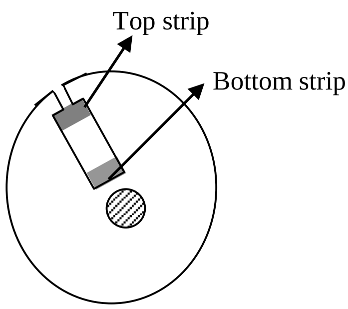
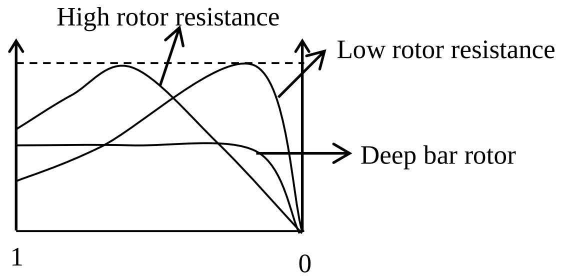


Fig. Deep bar rotor

- A much larger flux links the bottom elementary strip compared to the top elementary strip.

- The starting reactance (50-Hz reactance) for the bottom strip is much larger than that of the top strip. Therefore the current in the top strip is much more than the current in the bottom strip, because of its lower reactance.
- The current density progressively increasing while moving upwards from the bottom strip
- Non uniform current distribution causes greater ohmic loss, effective bar resistance becomes much more than its dc resistance.
- As the rotor speeds up to a value close to synchronous, the rotor frequency becomes very low. Now the reactance of strips becomes almost equal and current densities become nearly uniform so that it offers a resistance almost equal to its dc value.
- A deep bar rotor has low starting current, a high starting torque and a low running resistance.
- It gives good starting as will as good running performance



(2) Double cage rotor:

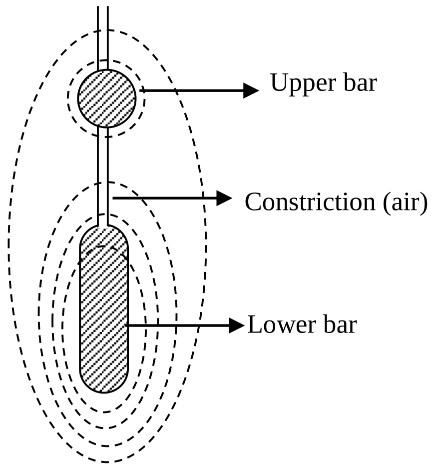


Fig. Slot-leakage flux pattern
for double cage rotor

- The upper bars have a smaller cross-sectional area than the lower bars and consequently a high resistance.
- The outer cage has high resistance and low reactance while the inner cage has low resistance and high reactance.
- Therefore, in the starting, the current is mainly confined to the outer cage with a consequent decrease in starting current and increase in starting torque.

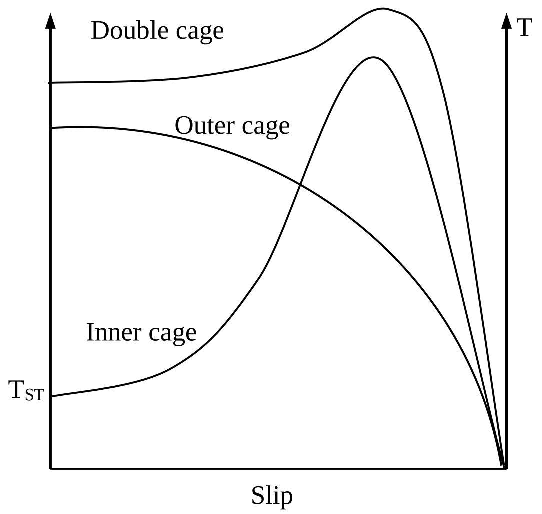


Fig: Torque – Slip characteristic- double cage IM

- Double cage induction motors has superior T-S characteristics.

Crawling

In, particularly the squirrel-cage type, sometimes exhibit a tendency to run stably at speed as low as one-seventh of their synchronous speed N_s. This phenomenon is known as crawling of an induction motor.

This action is due to the point that the a.c. winding of the stator produces a flux wave, which is not a pure sine wave. It is a complex wave consisting of a fundamental wave, which revolves synchronously and odd harmonics like 3^{rd}, 5th and 7^{th} etc. which rotate either in forward or backward direction at $N_s/3$, $N_s/5$ and $N_s/7$ speeds respectively. As a result, in addition to the fundamental torque, harmonic torques are also developed, whose synchronous speeds are 1/nth of the speed for the fundamental torque i.e. N_s/n, where n is the order of the harmonic torque. Since 3^{rd} harmonic currents are absent in a balanced 3-phase system, they produce no rotating field and, therefore, no torque. Hence, the total motor torque has three components:

(i) Fundamental torque, rotating with the synchronous speed N_s

(ii) 5^{th} harmonic torque rotating at $N_s/5$ speed and

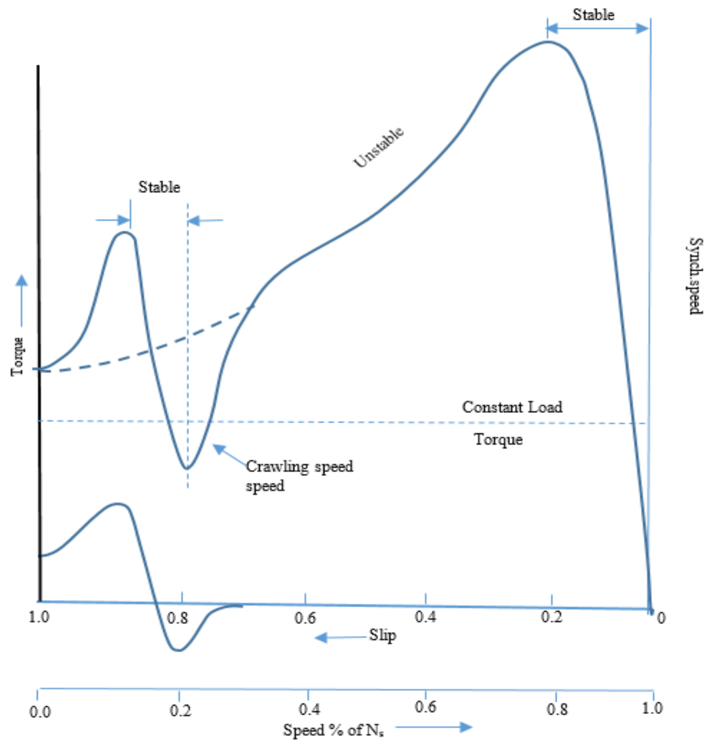
(iii) 7^{th} harmonic torque, having a speed of $N_s/7$.

Now, the 5^{th} harmonic currents have a phase difference of $5\times = 600^0 = -120^0$ in three stator windings. The revolving field, set up by them, rotates in the reverse direction at $N_s/5$. The forward speed of the rotor corresponds to a slip greater than 100%. The small amount of 5^{th} harmonic reverse torque produces a braking action and may be neglected. The 7^{th} harmonic currents in the three stator windings have a phase difference of $7 \times 120^0 = 2 \times 360^0 + 120^0 = 120^0$. They setup a forward rotating field, with a synchronous speed equal to $1/7^{th}$ of the synchronous speed of the fundamental torque.

If we neglect all the higher harmonics, the resultant torque can be taken as equal to the sum of the fundamental torque and the 7^{th} harmonic torque, as shown in fig. it is seen that the 7^{th} harmonic torque reaches its maximum positive value just before $1/7^{th}$ synchronous speed Ns, beyond which becomes negative in value. Consequently, the resultant torque characteristics shows a dip which may become very pronounced with certain slot combinations. If the mechanical load on the shaft involves a constant load torque, it is possible that the torque developed by the motor may fall below this load torque. When this happens, the motor will not

accelerate up to its normal speed but will remain running at a speed, which is nearly 1/7th of its full-speed. This is referred to as crawling of the motor.

By proper choice of coil pitch and distribution of coils while designing the winding, the possibility of the presence of harmonics in the air-gap flux wave is either made to zero or reduced to a very low value to eliminate the crawling effect



Cogging or magnetic locking

The motor of a squirrel-cage motor sometimes refuses to start at all, particularly when the voltage is low. This happens when the number of stator teeth S_1 is equal to the number of rotor teeth S_2 and is due to the magnetic locking between the stator and rotor teeth. That is why this phenomenon is sometimes referred to as teeth-locking.

It is found that the reluctance of the magnetic path is minimum when the stator and rotor teeth face each other rather than when the teeth of one element are opposite to the slots on the other. It is in such positions of minimum reluctance that the rotor tends to remain fixed and thus cause serious trouble during starting.

Cogging of squirrel cage motors can be easily overcome by making the number of rotor slots prime to the number of stator slots.